UCRL- 91744, Rev. 1
PREPRINT

ON THE EXTRAGALACTIC ORIGIN OF GAMMA-RAY BURSTS

Montgomery Johnson
Edward Teller

THIS PAPER WAS PRESENTED AT
THE QUANTUM THEORY AND THE STRUCTURES
OF TIME AND SPACE 6 SYMPOSIUM
TUTZING, GERMANY
JULY 2-5, 1984

November 2, 1984

Lawrence Livermore Laboratory

DISCLAIMER

ON THE EXTRAGALACTIC ORIGIN OF GAMMA-RAY BURSTS*

Montgomery Johnson and Edward Teller

Delivered by Edward Teller in Tutzing

July 1984

The subject about which I am going to talk I have discussed for a few years with my good friend Montgomery Johnson. Recently he died. Our attempts to clarify the origin of the short gamma-ray bursts that has puzzled astrophysicists for a decade was Montgomery's last scientific endeavor. The report given in this talk is a small and insufficient memorial to a wonderful man and a scientist whose fame never approached the measure that his substantial accomplishments deserved.

Detectors of gamma-rays carried by satellites and later by high-flying balloons showed the existence of events lasting from fifteen milliseconds to about a hundred seconds, arriving from all directions in space. A few hundred events have been observed in a little more than a decade. The energy of gamma-rays range from a few kilovolts to millions of volts. Recent evidence indicates that considerable energy may be carried at least in some cases even above 10 MeV. But the bulk of the energy appeared to be emitted between 100 and 200 KeV. The observed intensities range between 10^{-3} and 10^{-7} ergs/cm^2.

Less intense events occur with higher frequency. The distribution is consistent with the assumption that the events have a uniform distribution in

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

space. The number of events N(I) having an observed intensity greater than I changes as $I^{-3/2}$. Indeed, if one oversimplified the situation by assuming all events to have the same intrinsic intensity, then the observed intensity will vary as $I \approx r_\gamma^{-2}$ (r_γ being the distance of the event). The number of events greater than I will vary with $r_\gamma^3 \approx I^{-3/2}$. This regularity breaks down near the lowest observed intensities, the low intensity events being five to ten times less frequent than the relation would indicate.

The simple facts about intensity distribution are compatible with two extreme assumptions but exclude intermediate hypotheses. Either the events occur in our own galaxy in a region smaller than the thickness of the galaxy or they are of extragalactic origin and come from distant galaxies. Practically all attempted explanations have made the former explanation which requires that a mass of approximately 10^{20} grams impinges on a neutron star (assuming a near to 100% conversion of gravitational energy available on the surface of the neutron star or 10^{20} ergs/gram into gamma-rays which, of course, is unrealistic). In case of an extragalactic origin, the neutron star must attract and convert, as we shall see, about 2×10^{30} grams or 10^{-3} of the solar mass. It is perhaps the size of such events which deterred a detailed discussion of this alternative. Montgomery Johnson and I have tried to assume these big collisions, explore the consequences, and I shall talk about this extragalactic hypothesis.

A singular event was observed on March 5, 1979. A precise determination of location based on observation from several satellites, even as far away as Venus, located this event within a supernova remnant in the large Magellanic cloud, at a distance of more than 10^5 light years. This lends plausibility to the assumption that a neutron star is one participant. The duration of the event was only one-third of a second and the observed intensity is the largest on record. The observation does not fit well into either model. If one assumes a galactic origin, the actual energy release is 10^4 times the usual figure. If one believes in an extragalactic origin, the intrinsic energy is 10^{-7} times the usual value. In the first case we deal with a truly rare event; in the second, the occurrence would be unobservable at a distance of more than 10^8 light years where, as we shall see, the most intense observed gamma-ray pulses have their origin. Thus, further discussions of this event will be omitted.

The qualitative model used by Montgomery Johnson and myself is the following. A stellar object approaches the neutron star to within the Roche limit, R_R, where the inhomogenity of the gravitational force due to the neutron star tears the approaching star apart. The material falling on the neutron star performs after the collision process a turbulent motion which approaches the limit of being supersonic and relativistic (with maximum velocities in the neighborhood of c/3). Such motions promptly convert much of their energy into equilibrium radiation which, however, varies from region to region. Thus a total spectral distribution results which is considerably broader than a black-body radiation. Radiation moves with the material which provides the inertia at a velocity not much smaller than c. Thus a great fraction of the material arrives in rapid succession near the surface from where the radiation may be emitted. However, the process continues only as long as the collision partner provides fresh "rain" to impinge on the neutron star.

The objection has been raised that two light quanta possessing in their rest-frame an energy of ~2 mC^2 (m is the mass of the electron) will be scattered by each other. This will wipe out the deviations from the black-body spectrum. In this way a limit would be imposed on the intensity of the gamma-rays and thus on the distance of the event. If, however, regions of different temperatures are separated in space, scatterings will occur only in the thin region of the interface and the objection no longer holds.

Another striking property of the gamma-ray bursts is the rapid variation of their intensity with time. Tenfold changes are generally observed within a millisecond in which material may move 100 km or ten times the radius of the neutron star. Even more rapid changes might occur, but these are beyond present means of observation. The average envelope of intensities may show one, two, or three broad maxima lasting for seconds. All this is in agreement with a turbulent source of the radiation.

Essential information may be obtained from the duration of the event. This time is determined by the time of passage of the star that impinges on the almost point-like neutron star through the Roche limit. A head-on collision will give the minimum time limit $2R_s v_R^{-1}$, where $2R_s$ is the diameter of the star which approaches the neutron star, and v_R is the relative velocity at the Roche limit. Let M_n be the mass of the neutron star. Then the difference of the accelerations due to the presence of the neutron star at the proximal and distal positions of the approaching star can be written

$$GM_n \left[\frac{1}{(R_R - R_S)^2} - \frac{1}{(R_R + R_S)^2}\right] = \frac{4GM_n R_R R_S}{(R_R^2 - R_S^2)^2}$$

This difference tends to tear the approaching star apart. The star is held together by the vector-difference of accelerations due to the mass, M_s, of the star itself at opposite surface points on the star which is $\frac{2G\,M_s}{R_S^2}$. Setting these two quantities equal gives the Roche radius, R_R (the radius of the neutron star can be neglected).

$$\frac{2\,M_n\,R_R}{(R_R^2 - R_S^2)^2} = \frac{M_s}{R_S^3} \quad \text{or} \quad \frac{2X}{(X^2-1)^2} = \frac{M_s}{M_n} \quad \text{where } X = \frac{R_R}{R_S}.$$

If $R_S^2 \ll R_R^2$ one obtains the simple, well known relation $2\frac{M_n}{R_R^3} = \frac{M_S}{R_S^3}$. This means that if twice the mass of the neutron star is uniformly distributed over a sphere of R_R radius the average density of the incoming star is obtained.

If we now assume $M_S = M_\Theta$ (i.e., the mass of the sun), $R_S = R_\Theta$, $M_n = 1.4\ M_\Theta$. The simplified formula yields $R_R = 1.4\ R_\Theta$ so that R_S^2 cannot be neglected. The accurate formula gives $R_R = 1.8\ R_\Theta$. Therefore, the simplified formula does not lead us completely astray. (It is valid for $M_S/M_n \ll 1$). It should be noted, however, that the implicit assumption of the impinging star reaching the Roche limit with little distortion is not a good approximation.

These considerations lead to the conclusion that the collision partner of the neutron star must be a dwarf. Indeed, for $M_n = 1.4\ M_\Theta$ and $R_S = R_\Theta$ the time $2R_S\ v_R^{-1}$ becomes more than 2000 seconds, which is much too long, and if the star does not approach in a purely radial direction the duration is even longer. On the other hand, for Sirius B the duration is 1.5 sec for radial incidence. For white dwarfs whose mass is less than M_Θ the collision times can be easily tripled. For a red dwarf with $M_S = 0.1\ M_\Theta$ the radius will be $R_S = 70{,}000$ km (approximately $0.1\ R_\Theta$ so that the central temperature can be maintained and thermonuclear reactions can proceed). In this case, R_R will be 20,000 km. For the relative velocity we get $v_R = 1.5$ km/sec and the collision times are a little longer than 100 sec, the observed maximum. Smaller red dwarfs with their higher densities will give shorter collision times and black dwarfs, in which the heating of gravitational contraction never has led to substantive thermonuclear reactions, give even shorter times. Since the number of stars increase when their mass decreases, collision with black dwarfs may actually play a role in producing observed gamma-ray bursts.

After the Roche limit is passed, one may get a crude estimate of further events by assuming that each volume element falls onto the neutron star without interacting with the others. The volume elements then follow parabolic orbits and the diameter of the approaching star shrinks roughly as $r^{1/2}$ perpendicular to the motion, where r is the distance from the neutron star. The cross-section decreases as r. On the other hand, the velocity increases as $r^{-1/2}$ and, therefore, the linear dimensions in the radial direction increase as $r^{-1/2}$. Thus the density increases as $(r \times r^{-1/2})^{-1} = r^{-1/2}$.

We now can give some justification for considering the motion of the volume elements as roughly independent. The $r^{-1/2}$ variation in density gives rise (using the degenerate equation of state) to a $r^{-5/6}$ variation in pressure and since the cross-wise dimension changes as $r^{1/2}$ the pressure gradient will change as $r^{-8/6} = r^{-4/3}$. This pressure gradient is partly cancelled by the self-gravitation of the star. The attractive force from the neutron star, on the other hand, changes as r^{-2}. This force is apt to predominate.

Sirius B with 10^{-2} $R_\odot$ and 10^6 times the density of the sun (which is 1.4 gm/cm^3) will increase in density 36 fold if it hits the surface of a neutron star with a 10 km radius. This gives a density of 5×10^7 gm/cm^3 and an energy density (assuming a gravitational potential of $0.1 \times C^2$) of 4.5×10^{27} erg/cm^3. In equilibrium practically all energy will appear as radiation. The shock that accompanies stagnation at perpendicular incidence will increase the density and the energy density by another factor 4 and a radiation temperature of 3.4 MeV will result. Of course the surface of the neutron star in the state of collision will in general not be visible, though in the resulting turbulent motion glimpses of it may be obtained.

In the turbulent motion material velocity and sound velocity will be comparable. The velocities will reach 1/3 C so that relativistic effects cannot be disregarded and any material--distributed on the average within a 1000 km sphere--has a chance to reach the external radiation surface in 100 milliseconds or less. Assuming turbulent elements of a ten kilometer dimension, strong intensity variations in less than a millisecond can be expected. At a 1000 km radius, densities of 2×10^7 gm/cm^3 may be found (which includes a four-fold shock-compression) and an energy density of 2×10^{25} may be assumed. This would give a radiation temperature of 0.6 MeV. The bulk of the observed spectrum corresponds to a temperature a little less than one-tenth this value. Most emission probably occurs after considerable expansion.

The above figures hold for Sirius B and have been presented for the sake of illustration. Higher temperatures may be obtained from white dwarfs of even higher density. On the other hand the predominance of lower frequency radiation from regions further removed from the surface of the neutron star is not surprising. It would be of great interest to obtain the time dependence of radiation above 1 MeV and 10 MeV. Short bursts, coinciding with intensity maxima should be expected.

Let us look more closely at the development of the collision near the Roche limit. We shall use a coordinate system that moves along with the free-falling center of the approaching star. The inhomogenity of the gravitational field of the neutron star will cause a crosswise contraction and a lengthwise expansion which sets in even before the Roche limit is reached. Taking into account the self-gravitation of the incoming star, fission may occur and two separate pieces will fall onto the neutron star. This might correspond to two separate, relatively broad, maxima superposed on the rapid variation of intensity. This has been often observed. Even triple fission might ensue, giving rise to three maxima in the intensity envelope. Such a fission process is of course a deviation of the assumed independent behavior of the volume elements. The shortest observed event, lasting 15 milliseconds, might be perhaps due to a fission process where only the innermost small piece of the incoming star reached the surface of the neutron star. Verification and the working out of details will require extremely complicated numerical calculations.

Do most events come from white dwarfs or from red dwarfs? Are even more events due to black dwarfs? The ratio of the abundance of these stars is as 1 to 10 to 100 (the last figure is quite hypothetical). The masses are roughly in the opposite ratio and so would be the expected inherent intensities. This difference is further enhanced by the greater radii of the red dwarfs which has the consequence that a very great proportion of red dwarf has too great an angular momentum and goes past the neutron star without participating in the gamma-burst. This holds to a lesser extent even for the dense white dwarfs. On the other hand, it suffices for gamma emission if the material of the incident star does not hit the neutron star but only the material already deposited on it. Furthermore, streams of matter bypassing the neutron star on opposite sides will be deflected and are apt to collide behind the neutron star, losing their angular momenta and then falling toward the neutron star. Still, considerably higher intensities are to be expected from the white dwarfs than from the two other categories and so collisions of white dwarfs can be seen from greater distances. Thus we believe that most observed events may be due to white dwarfs. This argument is connected with the $I^{-3/2}$ dependence of N(I) which means that (for instance) an event of four times greater intensity, being seen from twice as great a distance has an eight times greater frequence of occurrence in the observations. The black dwarfs, which are of greatest abundance, may compete with the white dwarfs because, though having smaller mass they have a greater density than the red dwarfs and thus a greater fraction of their mass will participate in the gamma-ray emission process. Longer gamma-ray emission processes approaching a duration of 100 seconds may well be due to black dwarfs. This, of course, would mean that all gamma-ray bursts are due to collisions of a neutron star with a degenerate partner.

It has been suggested that magnetic fields around the neutron stars which could have the strength of 10^{14} gauss could deflect the masses falling on the neutron star. For white dwarfs this cannot be important. For red dwarfs (if they play a role) and for black dwarfs the magnetic field may have to be taken into account. In the case of white dwarfs the approaching matter having a high energy-density will penetrate the magnetic field by producing instabilities which may compress the magnetic field into high field-strength regions between which the material can reach the neutron star without being strongly deflected. In any case the magnetic fields would accelerate the onset of turbulence.

Impact by high density matter may send irregular strong shocks deep into the neutron star. These will not reach the depth where neutrons predominate but would penetrate to the region where the proton-to-neutron ratio is substantially diminished. Some of that material may be ejected from the neutron star and neutron-rich unstable nuclei may be mixed into the in-falling material. It would be of interest to look for their effects.

Finally, we must obtain some estimate of the frequency with which such events may occur outside our galaxy. Such an estimate is made difficult because the needed binary collisions occur most frequently in regions where the number of stars per unit volume is greatest. Our knowledge of such regions is incomplete. There are, however, studies about globular clusters and the results can be easily generalized.

In a simplified fashion let us consider N stars of mass M distributed more or less uniformly in a volume of R^3. Then using the virial theorem the average velocity v of the stars will be given by

$$v^2 \approx \frac{GNM}{R}$$

where G is the gravitational constant.

The number of close collisions that one star makes per unit time is approximately

$$\left(\frac{GM}{v^2}\right)^2 \frac{N}{R^3} \; v$$

The total number of collisions per second is obtained by multiplying by N (with the neglect of a factor 1/2 which is no worse than other simplifications we have committed). This gives for the total number of collisions per second

$$\left(\frac{GNM}{v^2}\right)^2 \frac{v}{R^3} = \frac{v}{R}$$

where the equation following from the virial theorem was used. The remarkably simple result is that while one star crosses the cluster, just one strong collision between all the stars will have occurred.

Globular clusters evaporate in a time comparable to the lifetime of the galaxy. A close collision may give enough energy to one star so that it can escape from the cluster. Actually evaporation occurs about 10 times as fast due to cumulative effects of distant collisions which give a logarithmic contribution. That globular clusters are globular is probably due to this evaporation process in which stars with high angular momentum evaporate faster than those with low angular momentum. This eventually leaves a residue whose angular momentum is zero and has, therefore, a spherical shape. (Galaxies would similarly become spherical in a time which is much longer than the age of the universe.)

If the globular clusters were formed (originally in a non-globular form) at the beginning of the galaxies, one must conclude that in the time that has passed more than 100,000 stars may have evaporated and more than 10,000 close collisions have occurred. Considering only close collisions between neutron stars and white dwarfs, we must remember that white dwarfs are 10^{-1} of all stars and neutron stars 10^{-2}. In order that a white dwarf should approach to within the Roche limit, the angular momentum is only about one-tenth of that needed for a close collision, that is one which produces a strong deflection. This leads to a collision parameter which is 10^{-1} smaller and a factor in the probability of 10^{-2}. Thus, in the age of the galaxy (or the universe) the number of gamma-bursters per globular cluster is 10^{-5} of all close collisions within the cluster. That means 10^{-1} gamma-bursters per globular cluster in the age of the universe. Since there are 100 globular clusters associated with our galaxy, one would get one event in about 10^{9} years per galaxy assuming that in regard to globular clusters our galaxy is typical.

In order to explain the observed facts, we need a frequency about 10^{2} times higher. Of course, our estimates have been quite crude* and, furthermore, there may be many other regions in the universe with greater number of stars per unit volume. Centers of galaxies and possibly globular clusters not

---

*In particular, the frequency of white dwarfs and neutron stars in globular clusters is apt to be greater than estimated from the numbers obtained near the sun. Indeed, they originate from stars heavier than the average and from globular clusters the light stars have preferentially evaporated. Furthermore, the number of globular clusters, including those that are invisible, is probably higher than assumed above. On the other hand, the collision cross-section for production of a gamma-burster has been assumed considerably higher than would follow for the simple equilibrium model used above. This has been done in part because near the center of globular clusters high densities are observed which are apt to lead the gamma-bursters without making a great contribution to evaporation. The situation is, indeed, complicated because the age of the universe is insufficient to establish full equilibrium according to statistical mechanics inside a globular cluster. All this shows that the figures given above are, indeed, only crude estimates.

associated with any galaxy might be considered. Since no coincidence in direction has been observed between gamma-ray bursters and visible galaxies, smaller clusters than galaxies, and in particular randomly distributed globular clusters might be reasonable candidates. For the following estimates we shall assume one event in 10^7 years per visible galaxy, which indeed means that we managed to account only for about 1% of the observations.

One observes approximately one event in ten years with an intensity of 10^{-3} ergs cm^{-2} sec^{-1}. This must come from a volume containing 10^6 galaxies or approximately 10^{-5} of the volume of the universe. The corresponding distance is 1.5×10^8 light years and this would correspond to 2×10^{50} ergs emitted in the process. Making the extreme assumption that 10^{20} ergs/gm are emitted, that would require 10^{-3} $M_\odot$ of mass to be involved. This is an acceptable value since $M_S/10$ is the maximum energy available if all the stellar mass would have reached the surface of the neutron star and released the energy into gamma rays. Our figure corresponds to the energy released if the incident star would have reached a distance 10^2 times the radius of the neutron star or 10^3 kilometers. Of course, our estimates are obviously crude. Collisions with any star will occur approximately 10^2 times more often than we have just calculated. The corresponding signals are weak. It is not clear whether or not they play a role in observed gamma-bursts.

Considering now the deviation from the $N(I) \sim I^{-3/2}$ regularity, one can see that for the first factor of 100 in I, that is events between 1.5×10^8 light years and 1.5×10^9 light years, there is no observed deviation. For the next factor of 100 in intensity we would be running out of available distances. That N does not increase as rapidly with decreasing I as the formula would indicate there are four reasons: first, the curvature of space; second, the red-shift; third, that in the distant past there had been a lesser number of white dwarfs since these, once formed, will last practically forever; and lastly, that the number of neutron stars was probably also smaller (though some neutron stars may be destroyed by turning into black holes through accretion).

There is a relatively simple experiment that will decide whether gamma-ray bursts are extragalactic as Montgomery Johnson and I assume or whether they are of local origin. Weak events, presumably associated with bigger distances, are best observed by balloon flights. The thin layer of air above the balloon will filter out gamma-rays strongly deviating from the perpendicular. If we compare flights where this direction points toward the galactic plane with those where it points toward the galactic pole one can decide whether or not the weaker event are isotropic in direction. Indeed, if the gamma-bursts are of local origin, the lesser N(I) values found for small I would be explained by the events coming only from the neighborhood of the galactic plane rather than from all directions.

In case there is an event in one of our own globular clusters (assuming the validity of the model here presented) the intense gamma-radiation would not reach the earth and would not leave any lasting mark. The resulting fluorescence would, however, light up the sky with an intensity about 10^{-2} of sunlight, a spectacular occurrence if it happens at night. We expect such an event once in 10^{9} years. A similar event may originate in the galactic center.

For us it is more important that, in case our interpretation proves right, investigation of gamma-burst of low intensity will yield information about the early history of the universe and may help to decide among various hypotheses concerning the oldest question of science: how did the world start?